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STUDY OF A NUCLEAR ELECTRIC GENERATOR FOR SPACE

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1. INTRODUCTION

The possibility of using nuclear energy for the supply of electric /1* power to space vehicles have led the French Atomic Energy Commission to undertake a series of studies in this field, in view of the interest manifested by the National Center for Space Studies.

The present report is a résumé of an exploratory study done in 1964. It is the result of the collaboration between engineers from the following institutions:

(1) The French Atomic Energy Commission (Atomic Pile Management, Department of Pile Studies, Department of Physics Research and Metallurgy Department);

(2) The National Company for the Studies and Construction of Airplane Motors (Atomic Division).

II. ELECTRIC POWER NEEDS OF SPACE VEHICLES

The electric power needs of space vehicles are still not known with much accuracy. The power levels contemplated in the U.S.A. are widely scattered (from 0-300 kWe). There is of course a threshold below which the nuclear reactor becomes uninteresting. In this case recourse must be had to either solar cells or radioisotopes or chemical sources, depending upon the lifetime requirement. The value of the threshold, which will no doubt increase with the technical

*Numbers given in the margin indicate the pagination in the original foreign text.

progress made on these processes, can presently be established at a few kilowatts.

For such low power levels, and even for levels of up to a few hundred kilowatts, the size of the reactor and the investment in fissionable material cannot be less than a certain minimum which depends on considerations of neutrons, with a given set of temperature characteristics for the energy conversion circuit.

The need for a rigorous study has led us to preliminarily choose the generator power level. A short parametric study has permitted later to determine the law of variation of the masses as a function of the power level. For the purpose of the study a hypothetical nuclear reactor was chosen that furnishes a thermal power of 750 kW.

III. CHOICE OF THE ENERGY CONVERSION PROCESS

The absence of an environmental medium leads to the use of radiation as /3 a means of dissipating the cold source energy. It leads to temperatures and materials which are generally completely different from the usual temperatures and materials, if large radiator sizes have to be avoided. In addition, the possible uses of these sources (telecommunication satellites, remote probes) require large lifetimes, which can be chosen to be about 10,000 hours.

Since it is difficult to make rotating machines which fulfill these requirements in high temperature and lifetime without having any maintenance possibility, a strong interest in the so-called static energy conversion processes has arisen. These include the thermoelectric, thermoionic and magnetohydrodynamic processes. The following remarks are, however, in order, concerning the development of these techniques in the relatively near future.

The thermoelectric process is well suited to the low power levels, i.e., a few tens or even a few hundreds of watts. Above the kilowatt level the process would be likely to lead to weights and sizes drastically greater than those of the other systems, and seems therefore, not well adapted to nuclear reactors.

The thermoionic process would be a good candidate, performance-wise. It could even be designed without any rotating machine, provided a dc electromagnetic pump could be used for circulating the cooling fluid. However well known the characteristics of the individual diodes may be, their adaptation to nuclear reactions poses extremely serious technological problems, in particular, problems posed by the interconnections between the elements, by the nonuniform distribution of the neutron fluxes in the core, etc. The techniques developed evolve rapidly and one can count on future developments in this field.

As far as the magnetohydrodynamic conversion is concerned, the systems which use a conductive gas only aggravate the problems which originate from the temperature limitations of the core. Also, the demonstration in principle of MHD systems having converters which work in the liquid phase has not yet been made. The thermodynamic efficiency of the two-phase inductors is still very uncertain.

We therefore retain the more realistic conversion process by rotating machines. Amongst these, the Brayton cycle would permit to void several cycles (thermodynamic "loops") and to get rid of problems of phase separation in zero gravity fields. However, this choice of cycle would necessitate either temperatures of the hot sources which are too high for the gas turbines, or cold source temperatures which lead to completely prohibitive radiator dimensions. Figure 1 is taken from reference 10 and shows the surface area of the radiator per kWe produced as a function of the minimum temperature of the helium Brayton cycle or Rankine cycle.

As a first approach, we therefore use the usual Rankine cycle, in spite of its disadvantages, which we shall examine later.

IV. CHOICE OF THE TEMPERATURE AND MATERIALS

The radiation which cools down the cold source obeys the Stefan-Boltzmann law: /5

$$q/S = \epsilon \sigma T^4$$

where q/s is the radiated power per unit area

ϵ is the emissive power which is equal to 1 for the blackbody

T is the absolute temperature of the surface

σ is the Stefan-Boltzmann constant $= 5.76 \cdot 10^{-12}$ watts/cm^2/^{o}K^4

For example, for an emissivity equal to 1, the radiation is about:

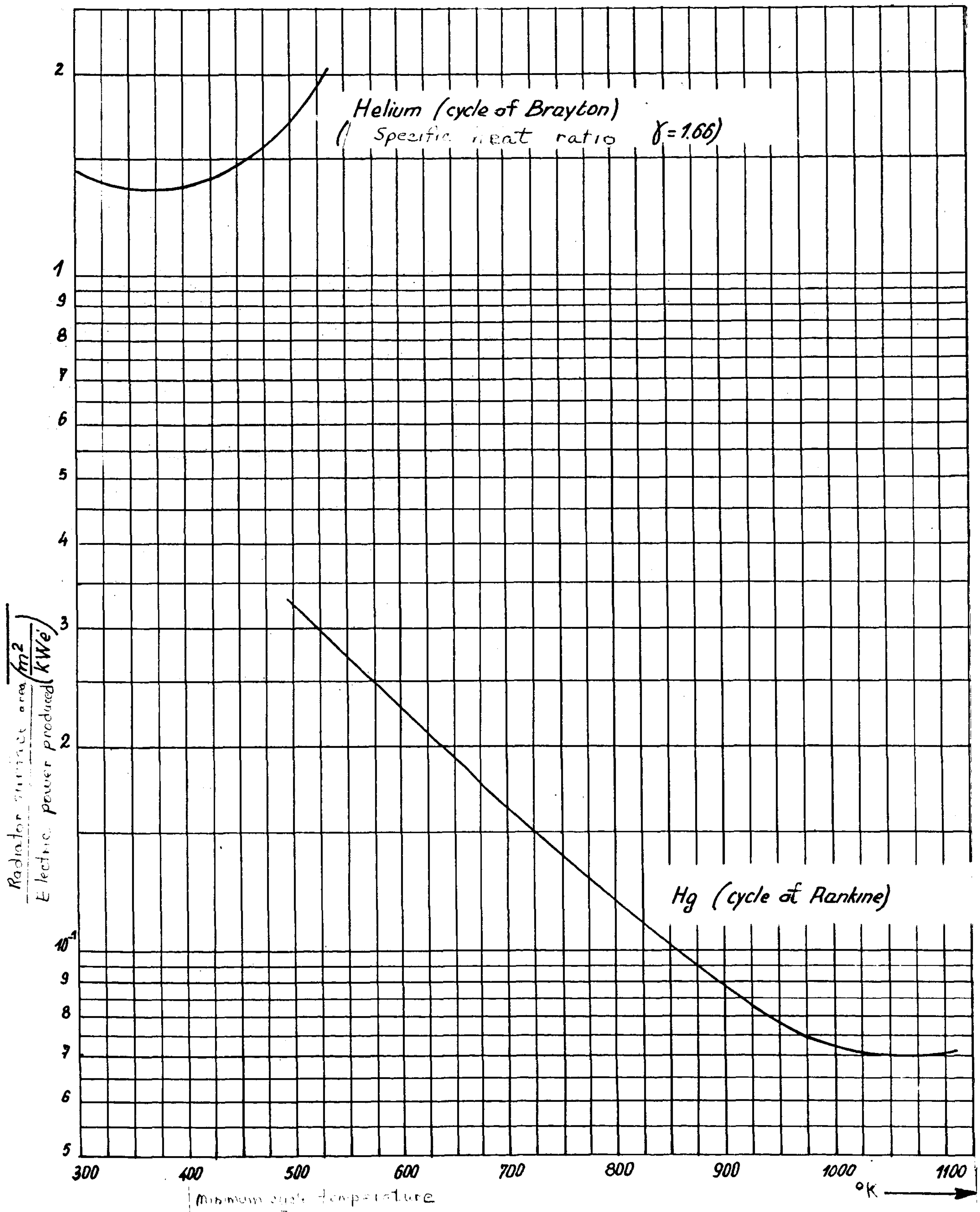
0.05 W/cm^2 at 300^{o}K

0.36 W/cm^2 at 500^{o}K

2.4 W/cm^2 at 800^{o}K

The first value shows that conditions similar to ground temperature are excluded. Even at high temperatures the radiator will still be in the tabulation of weights an important item which should be reduced by optimizing the temperatures of the cycle.

Figure 1 (p. 5). Radiator surface per kWe produced, for different cycles.


Helium (cycle of Brayton)
(Specific heat ratio $\gamma = 1.66$)
Hg (cycle of Rankine)
Radiator surface area / Electric power produced $\left(\frac{m^2}{kWe}\right)$
2
1
9
8
7
6
5
4
3
2
10^{-1}
9
8
7
6
5
300
400
500
600
700
800
900
1000
1100
°K
minimum cycle temperature

By taking the case of a Carnot cycle working between the hot and cold temperatures T_1 and T_2, the radiated power is written, with W being the useful power and η the efficiency:

$$\frac{W}{\eta}(1 - \eta) = W\frac{T_2}{T_1 - T_2} = K\ S\ T_2^4$$

where S is the surface area of the radiator.

From this we get: $S = \dfrac{W}{KK\ T_2^3(T_1 - T_2)}$.

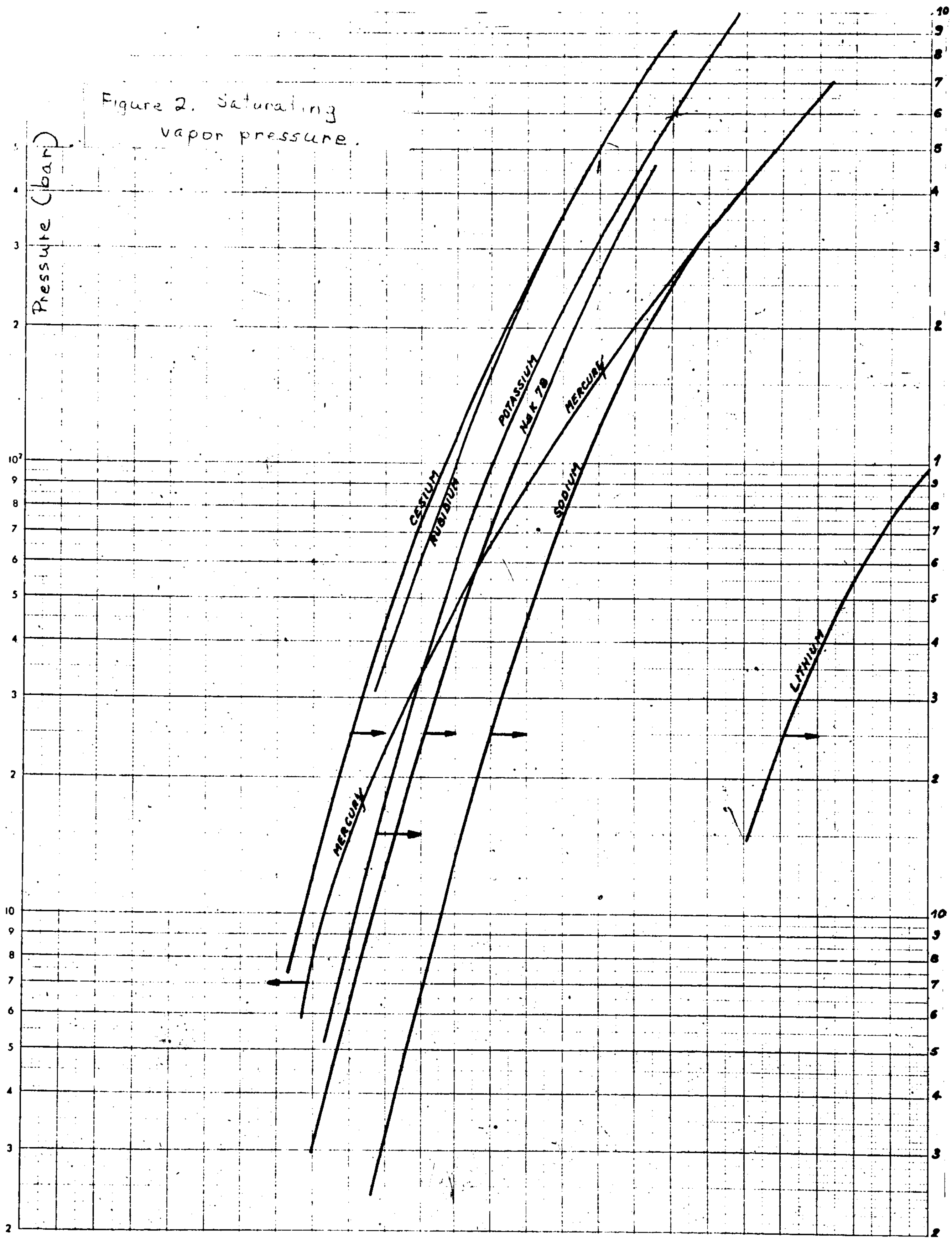
The area minimum when $T_2 = \dfrac{3}{4} T_1$.

The Carnot efficiency of this radiator having a minimum surface area is therefore only 25 percent.

In fact, the optimization calculations will be made by taking into account the effect of the various devices and of the antimeteoritic shield on the specific power (weight per KWe). The cycle efficiency will not be greater than the 25 percent mentioned above and one should not expect an overall efficiency much greater than 10 percent in a real situation. We are therefore led to choose the temperatures in a much higher range than for the classic engines. /6
This leads to abandonning water as the working fluid and to using a liquid metal instead. Figure 2 is a plot of pressure vs vaporization temperature for mercury, rubidium, cesium, potassium and sodium.

Figure 2 (p. 7). Saturating vapor pressure for various liquid metals.

Figure 2. Saturating vapor pressure.



Existing projects

Among the generators which are now in construction in the U.S.A. are the generators SNAP 2 (5 kWe) and SNAP 8 (35-50 kWe) which fall in the power range of interest to us. They have a reactor moderated by zirconium hydride, and cooled by the eutectic alloy of sodium and potassium, and a conversion circuit using mercury vapor.

The output temperatures of the reactor are 650° and 700°, and the boiling temperatures of mercury 500° and 575°. The average temperature of the radiators is about $310^{\circ}C$. Most of the materials employed are well known. For example, the reactor is made of a nickel base alloy (Hastelloy). A mixed uranium and zirconium hydride has to be made, and a hydrogen tight wall is required. The problems posed by corrosion by mercury are fairly well known and seem to have been effectively solved by the American scientists.

A study based on an analogous temperature scheme would have been instructive, but would not have permitted us to find the progress to be expected in the performance of the generator.

The announced weight (ref. 1) of SNAP 8 is 4.5 tons without protection, i.e., 150 kg per electric kW. This has led us to seek a reduction of the radiator weight by trying to use a reasonable increase in temperature. This weight, at least as far as the mercury systems are concerned, make up a large part of the total weight.

Our study concentrated on a reactor that would have an output temperature of $850^{\circ}C$, i.e., 150° more than for SNAP 8, and which would yield a thermal power of 570 kW. We shall see that these specifications lead to a solution completely different from SNAP 8, and closer to the solution studied in the U.S.A. and called SNAP 50, which works in a much higher temperature range ($1,110^{\circ}$).

The expected added weight is sizable but most of the structural materials and the working fluid must be changed. Indeed, if the strength against flowage at 10,000 hours is taken as a criterion for choosing the material (fig. 3), it is observed that Hastelloy can no longer be retained, and if the use of refractory materials is to be avoided, there remain only Inconel X and Nimonic 80 A, which are both nickel based alloys. A few alloys (H.S. 25 and Hastelloy R 41) have a better strength to flowage but cannot be retained, for the reactor at least, because of their high cobalt content.

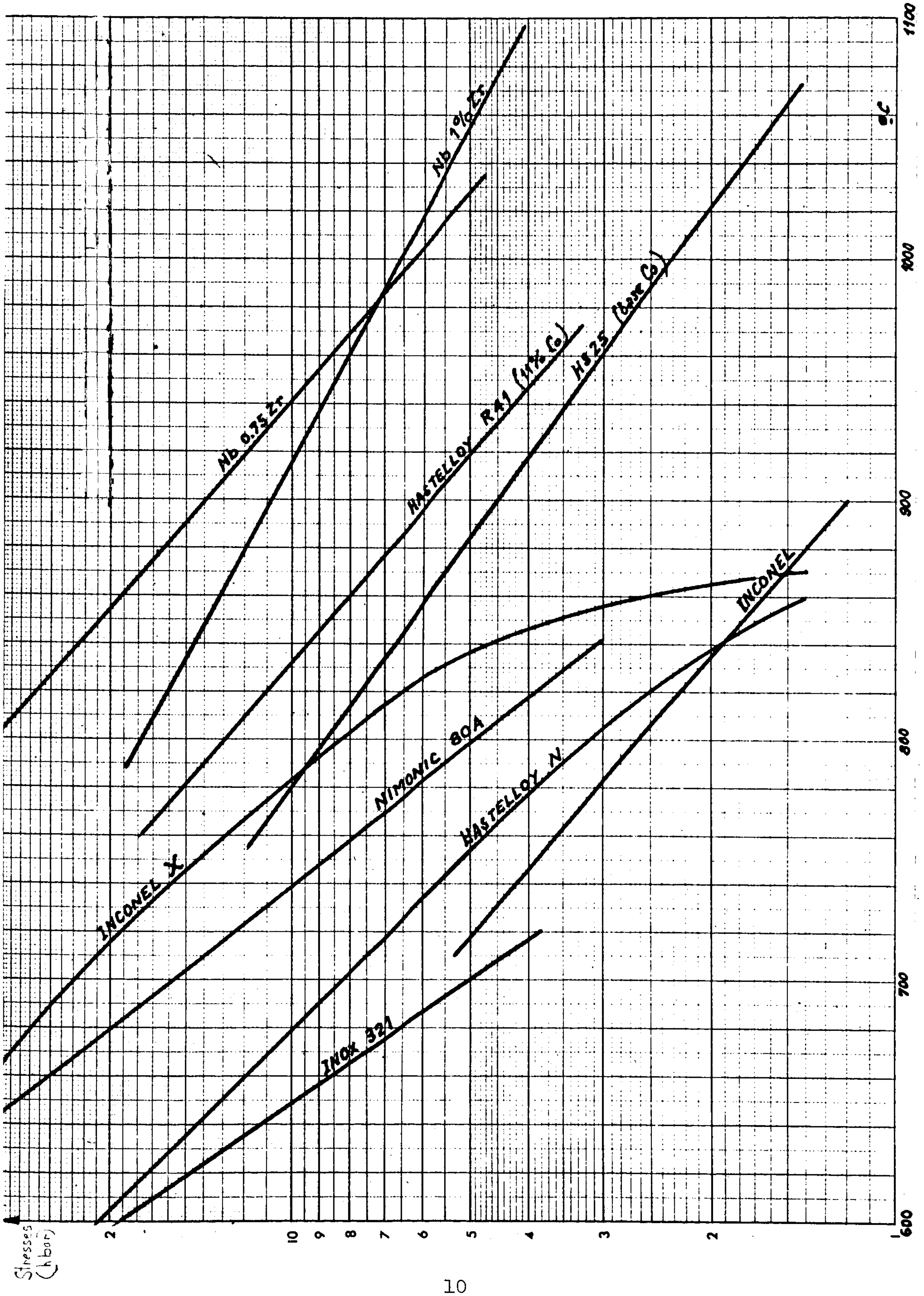
The temperature chosen is therefore in a limit zone for the nonrefractory materials, and is not high enough to justify the use of refractory materials.

Choice of the Working Fluid

The idea of having boiling taking place in the reactor proper has not /10 been considered. In particular the high changes of specific volume entailed by the formation of bubbles in a low pressure fluid do not permit to envisage a local boiling. This local boiling would lead to fluid losses in the pipes and thus tend to dangerously reduce the flow in these pipes. The necessity of having a cooling cycle in the reactor liquid phase leads to envisage using NaK as the primary fluid, with a pressure of a few bars in order to avoid local boiling.

The choice of a working fluid can be made from mercury, rubidium, cesium and potassium.

Figure 3 (p. 10). Rupture stresses for different alloys at 10,000 hours.


Nb 1% Zr
Nb 0.75 Zr
HASTELLOY R41 (11% Co)
HS 25 (50% Co)
INCONEL
INCONEL X
NIMONIC 80A
HASTELLOY N
INOX 321
°C
600
700
800
900
1000
1100
Stresses (hbar)
2
10
9
8
7
6
5
4
3
2
1

The turbine intake temperature is one of the important parameters of the optimization of the whole set. It should be chosen as high as possible. The good transfer of heat by liquid metals permits us to expect a difference of about 50° between the reactor exit temperature and the turbine intake.

Mercury would be in the region of interest to us, at the limit of its capabilities. At 750°C the vapor pressure is greater than 65 bars and the use of mercury would therefore lead to large thicknesses in the secondary circuit. It could, however, be had with less pressure and with greater superheat. We have not retained this topic of study, because it would forbid future development based on an increase of temperatures.

Potassium is, however, fairly close to its lower limit of use. The study of its working circuit has shown up a few difficulties. The optimization of the thermodynamical parameters leads to a turbine input temperature of 770° and a condensation temperature of 540° corresponding to a pressure of 0.079 bar.

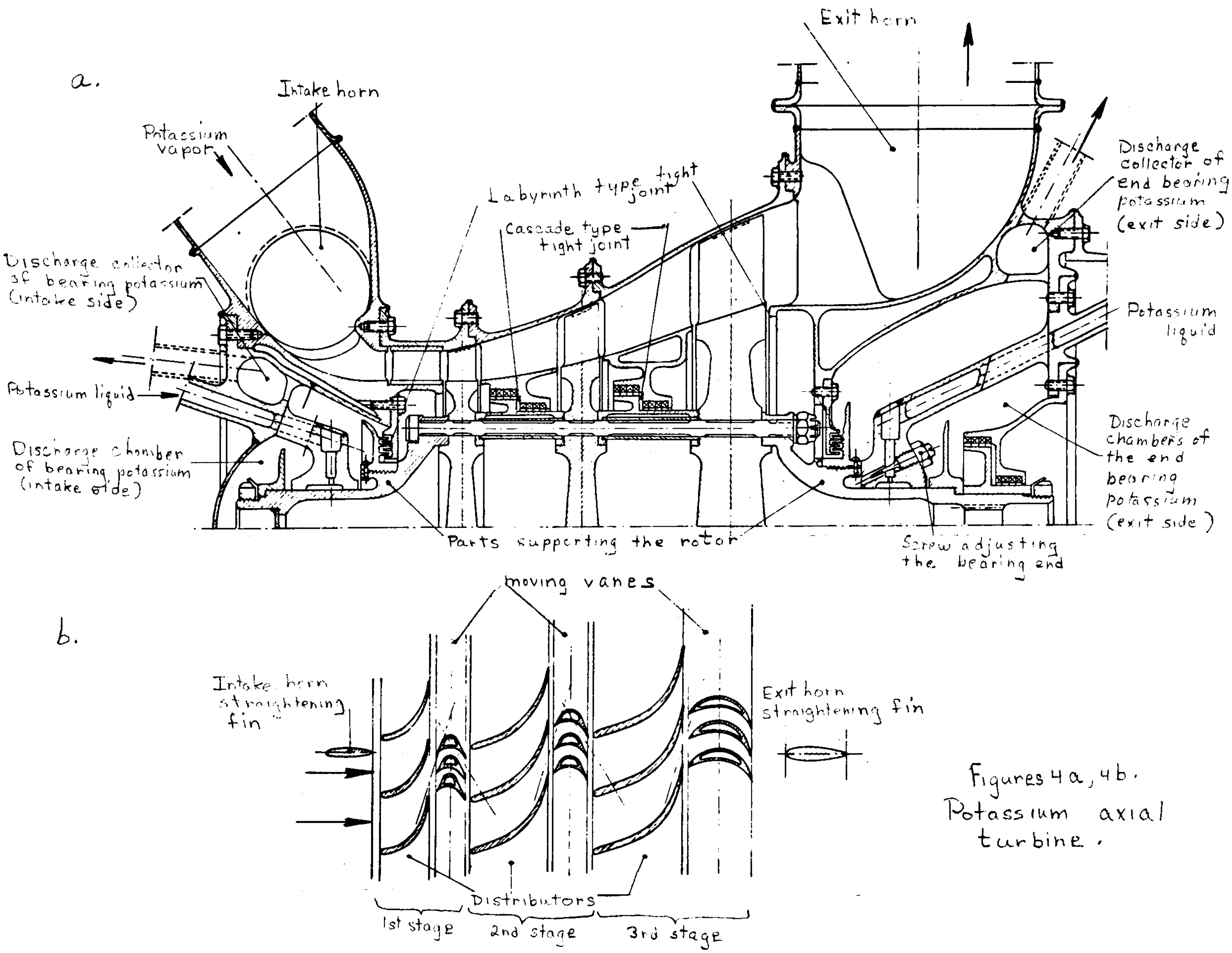
Under these conditions the specific mass of potassium is very low and leads, at the output of the 3rd stage, to a sizable volume rate flow (6.55 m^3/sec). The last turbine wheel will have to have a sufficient average diameter to permit this flow, and mechanical stresses are expected to be encountered. Figure 4 shows a cross section of a potassium turbine adapted to the working conditions under consideration.

Rubidium and cesium should be better adapted than potassium to the temperature range envisaged. We have, however, estimated that it would be more reasonable to gear this study to a working fluid which is better known and especially less expressive, namely potassium.

Figure 4 (p. 12). Turbine cross section.

a.

b.



Figures 4a, 4b. Potassium axial turbine.

Materials for the working circuit

The working circuit could be made of the same alloy as the primary circuit. It is possible that problems of erosion by potassium, and of mechanical stresses in the turbine, may lead to study relatively new materials, such as molybdenum alloys. More important experimental studies are needed in this field, of both the rotor and the bearings, since they pose a major problem. It would be useful to study hydrostatic bearings employing the same fluid as the working fluid. For example, the solution employed for SNAP 2 (ref. 1) consists in coupling to the same shaft both the turbine and the supply pump, with the alternator between the two. A certain loss of mercury vapor flows in the magnetic gap of the alternator. This unit, called "Combined rotating unit," has worked well for over 12,000 hours.

Radiator

A radiator for space is essentially made up of collectors and tubes /12
which carry the working fluid, of fins which radiate to space, and has a certain thickness of material around the tube to protect them against meteorites.

1. Shape

The radiator is important because of the geometry problems associated with it. Indeed, if one wants the maximum effective surface area one is led to the plane radiator which radiates from both sides. This solution has in the end not been retained for space vehicles because it cannot be adapted to the launching problems and requires a deployment, once in orbit, which would be technically difficult. The radiator having the shape of a conical body, with the possibility of a cylindrical extension, has the advantage of being easily protected against nuclear radiation by having it in the shadow cone of the nuclear shield. It can also serve simultaneously as a structural element and as a shield against meteorites for all the devices which are inside it (fig. 5). We emphasize that the angle of the frustum of cone will be determined from an optimization of the reactor and shield combination. Figure 6 shows a sketch of the radiator.

2. Choice of the Materials

For the frustum of cone of the radiator shell which is to shield against meteorites, the best material is beryllium, regardless of the temperature range envisaged. This material has indeed the best combination of specific weight and resistance to puncture by meteorites.

For temperatures of about 300°C aluminum can be used, since this material comes right after beryllium in the list of preferred materials for antimeteorite shield purposes.

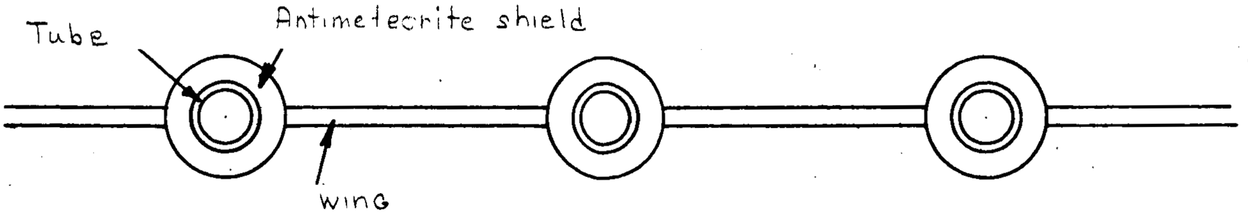
The tubes and the collectors are made either of stainless steel or or inconel, since the latter has the added advantage of having an expansion coefficient close to that of beryllium. The radiator fins are also used as structural element.

V. CHOICE OF THE REACTOR

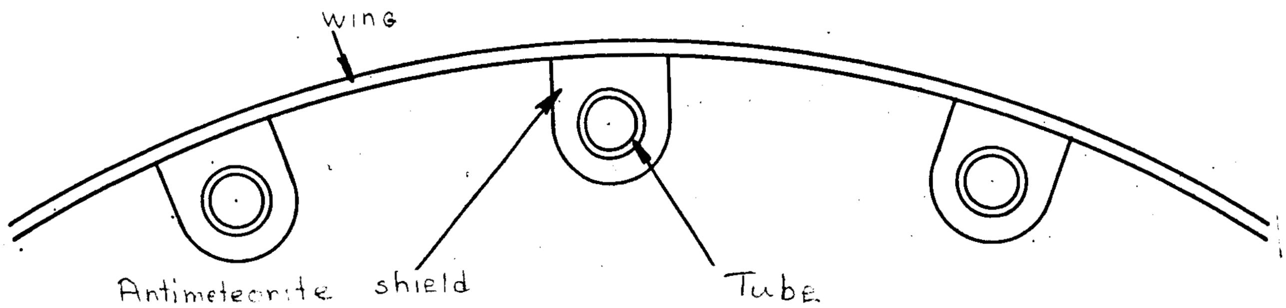
1. Thermal Neutron Reactor

The low wattage involved leads to the study of a thermal neutron reactor, which requires only a small investment in fissionable material. The size of the reactor affects not only its own weight but also the amount of necessary shielding. Small reactor sizes can be obtained by using a hydrogen material as

Figure 5 (p. 15). Radiator types.



Flat radiator



Circular radiator

Figure 5.

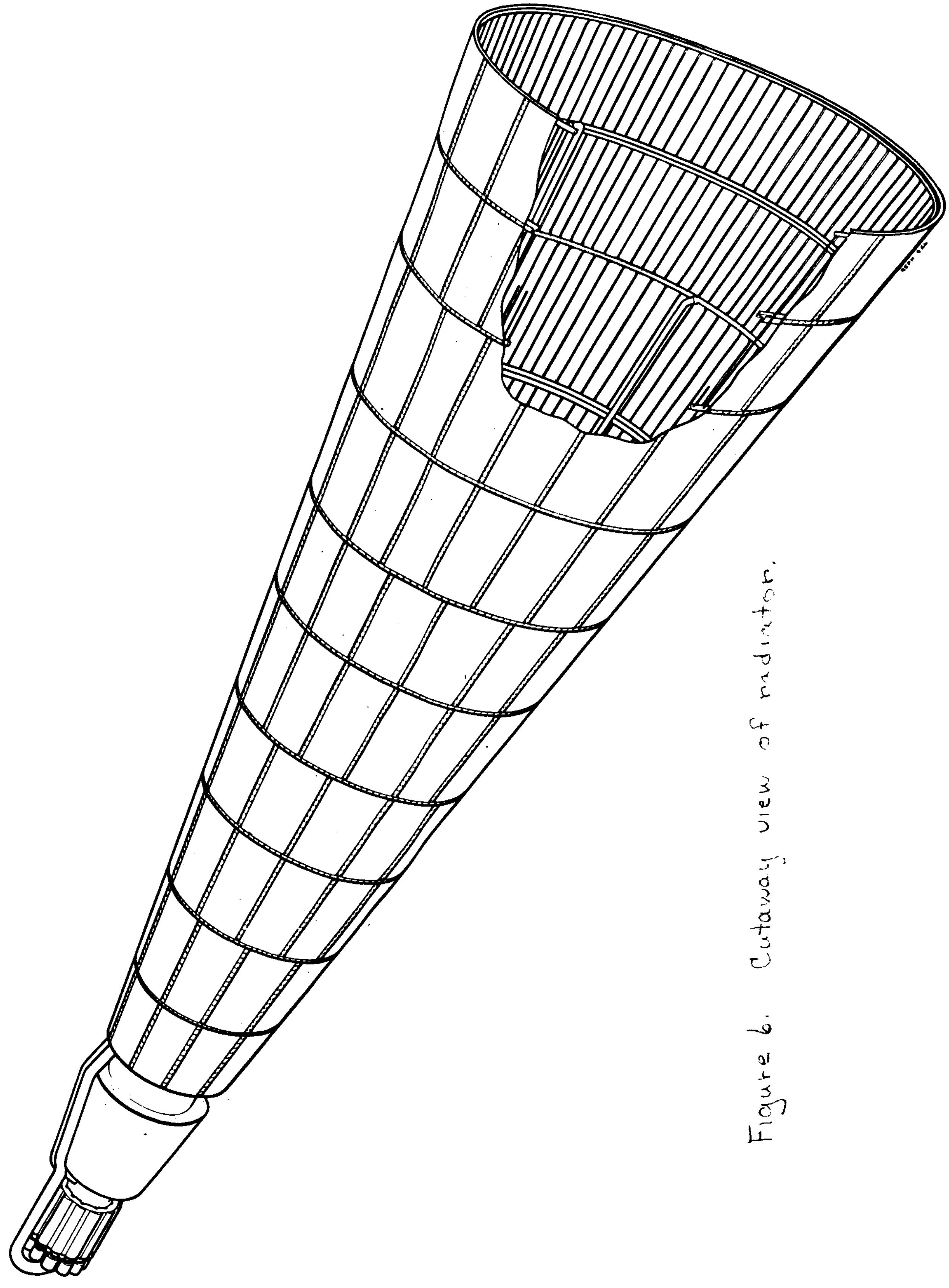


Figure 6. Cutaway view of radiator.

the moderator. The temperatures envisaged forbid the use of water, so a metallic hydride becomes mandatory. As far as the reflector is concerned, the scattering properties of beryllium and its mechanical behavior make it a good material.

The problem is then to find a metal of small capture scattering cross section with respect to thermal neutrons, with its hydride having a sufficiently low dissociation pressure at the temperatures employed. We are, anyway, forced to cover the cladding containing this hydride with a substance which is as much as possible impermeable to hydrogen. Some enamels can perform this duty, but their quality diminishes in general when the temperature is raised.

Up to around 700°C, zirconium hydride has all the qualities sought. /15
It is used in the reactors made by Atomics International but the temperatures of SNAP 8 (maximum temperature in the hydride 843°C, temperature at the reactor exit 704°C) is at the maximum temperature that this material can be used. Above the temperatures the dissociation temperature is such that the coatings will not be able to be sufficiently tight-proof.

Above 700°C, the properties of zirconium hydride become worse fairly rapidly and the best moderator becomes yttrium hydride (ref. 5).

1.1 Arrangement of the fuel elements

Since it is possible to make a mixed hydride of U-Zr, the best solution consists in making shielded homogeneous rods of fuel and moderator. The mixed hydride of Uranium and Yttrium cannot be made so that a heterogeneous solution must be thought of. However, the cladding of the moderator seems to pose in this case more serious problems than in the homogeneous solution. In addition, the sinking-in of the flux in the fuel rods enriched to maximum is very important (for rods 2.6 mm in diameter the disadvantage factor is greater than 4).

A homogeneous solution would therefore be preferable. It could be obtained by scattering in the yttrium hydride either uranium particles 150 μ in diameter and covered with a molybdenum protective coating, or uranium monocarbide particles coated with silicon carbide (ref. 6). Indeed, uranium carbide and uranium oxide are not chemically compatible with yttrium.

There remains then to develop a coating which would be sufficiently hydrogen tight at a temperature of from 850-900°C and a hydrogen pressure of about 0.1 bar, and to check the behavior under radiation of the fuel elements thus made. Preliminary tests have been made at C.E.A. in this field.

The reactor would be a right cylinder of 42 cm diameter containing 13 kg of U_{235} and having a total weight of about 350 kg.

This would be a useful solution provided a hydrogen tight shielding could be developed. It is possible that this solution may represent a temperature ceiling for hydride reactors.

Above 900° exit temperature the moderator should be beryllium or graphite, which leads to excessive sizes, even if the moderator is undermoderated.

2. Fast Neutron Reactors

The fast neutron reactors lend better themselves to high temperatures in piles of small size. Their only disadvantage is their high investment requirement in U_{235}, which is about 65 kg in our case (ref. 3). At the desired temperatures the usable materials are, as far as we know, uranium oxide UO_2 and uranium monocarbide UC. The latter has the appreciable advantage of having a higher volume concentration of fissionable nuclei than the oxide, with a ratio of about 1.4, in spite of the fact that the carbide is less known than the oxide.

An examination of the materials usable as reflectors has again shown the usefulness of beryllium. It is not advantageous to choose a reflector which strongly slows down the neutrons because a power peak is created by it in the elements around the core. If this peak is to be reduced to a tolerable value, we are led to reducing the concentration of fissionable nuclei of these elements and the size increases. The optimum seems to be a thickness of beryllium sufficient to permit the control of the reactor by moving sectors cut from the reflector. This thickness would not be sufficient to thermalize the whole spectrum at the intersurface between the core and the reflector. A thickness of 5 cm has seemed suitable, and with it, a right cylindrical reactor of 30 cm diameter is obtained in this way, weighing about 150 kg.

In addition the the high investment in fissionable material for this /18
fast reactor, a possible disadvantage could be its temperature effects.

In such a reactor more than half the neutrons ejected go out of the medium, the density decreases due to the expansions cause a marked effect. An average temperature coefficient of about -2 pcm/$^{\circ}$C due to this expansion effect can be expected.

Geometry effects are probably of little effect to cancel this power coefficient. It is probably possible to design the reactor core so as to avoid these effects.

In addition, a study of the regulation of the generator (ref. 8) has shown that the control of the power level of the pile can be insured by servo of the reactivity which is due to the pilot sectors at the pile exit temperature. This mode of control is effective because of the good thermal conductivity of uranium carbide and of the high exchange coefficient between the rod and NaK. The exit temperature reacts rapidly to a variation of the pile power.

VI. CONTROL AND STARTING PROBLEMS

We have seen that the control of the pile power level by the exit temperature was not only possible but very efficient, at least from a certain level of power on. The generator studied is normally designed to work at its nominal power level for a very long duration, i.e., about one year. The regulation goal will be to maintain a certain number of quantities constant, among which the electric power, by using as simple as possible a control scheme.

The secondary circuit can pose serious regulation problems, by having a one passage exchanger whose filling time is low. A model of the generator has shown that this unit remains stable provided the pump rates and the turboalternator load are kept constant, while the reactor exit temperature is regulated by the reactivity. In case of a disturbance, the temperatures of the conversion system come back to their original values. The presence of the radiator is stabilizing, because the radiated power of the radiator is only a function of the average temperature. The rate of flow of the turbine is a function of the vapor pressure which is sensitive to the exchange level. This fact is also stabilizing provided the other parameters are maintained constant.

The regulation of such a unit does not in principle show any difficulty. One of the essential problems to solve in this field consists in constructing accurate and reliable flow rate regulating devices.

The starting of this generator can only be done when in orbit. We could think of bringing the whole set of circuits to a temperature close to the working temperature, without using the reactor, for example by driving the prime pump by an auxiliary source. The amount of energy furnished would require batteries too large and the reactor must participate in the temperature rise. The speed of this rise depends on the thermal strength of the various components of the system. This speed will permit us to draw up a program of power rise and of reactivity input with temperature feedback. The starting of the secondary circuit poses serious problems of inserting the working fluid. It seems possible to stock up solid state potassium in the exchanger and to have calibrated membranes which open up when the pressure is sufficiently high. The reheating of the turbine must also be studied.

These questions concerning starting while in orbit can only be legitimately studied by experiments.

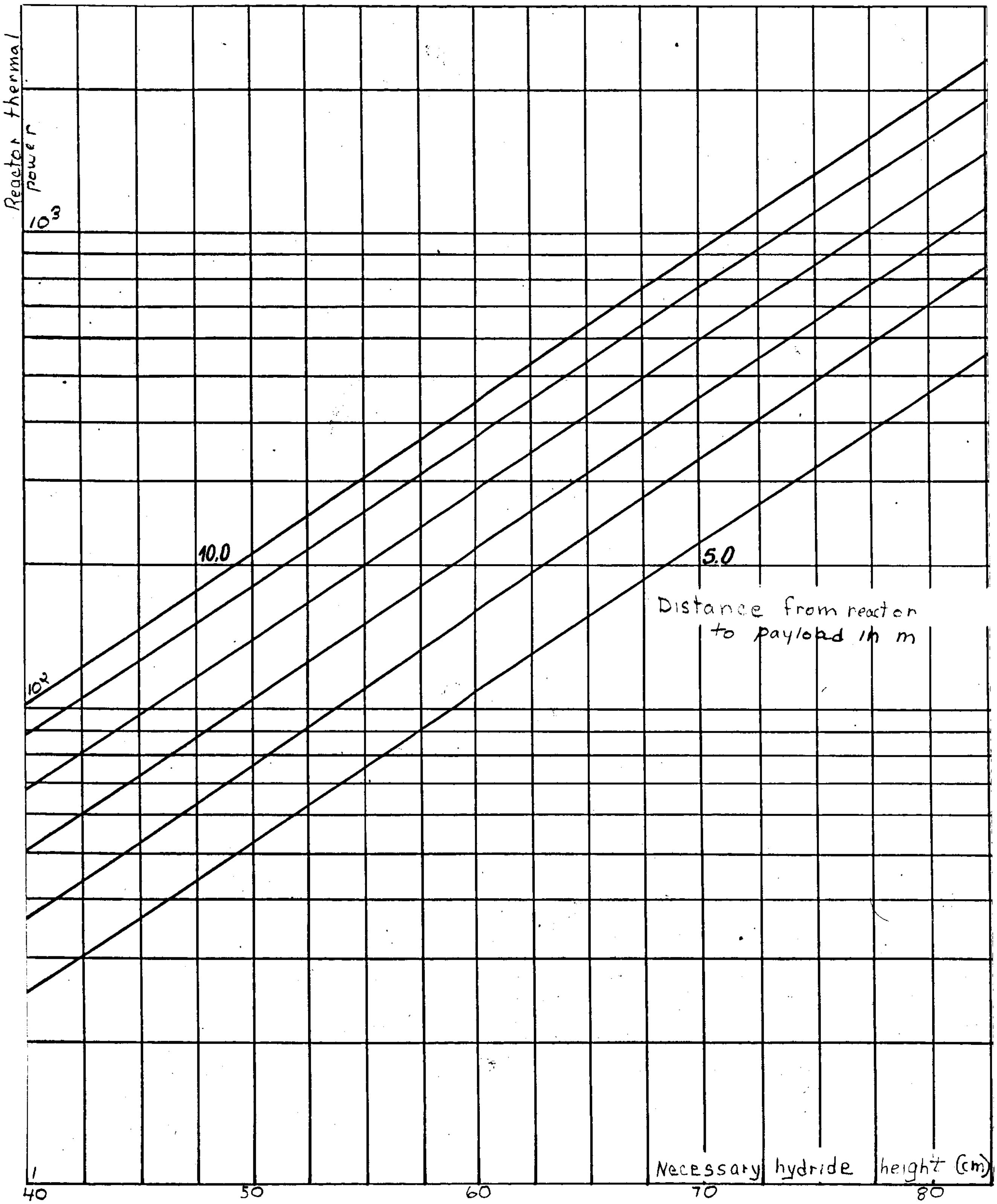
VII. PROTECTION AGAINST RADIATION

We have not yet mentioned the problem of using the generator in the /21 vicinity of a manned vehicle. The protection has been studied in the case where the generator supplies a transistorized communication relay. The tolerated doses on the payload have been determined in this case (ref. 9). The slowing down of the neutrons originating from the reactor requires a high hydrogen content in the medium. Again, a compound having a high proton density must be found, with a small dissociation pressure at the temperatures envisaged. In addition, the search for a minimum weight will lead to a compromise between the proton density and the specific weight of the medium. Lithium hydride satisfies well these requirements.

The gamma protection material must have both a high density and a good temperature behavior, and tungsten meets these conditions.

The calculation of the protection takes into account the presence of the activated NaK in the boiler located outside of the nuclear protection. Figures 7 and 8 show curves giving the necessary protective thickness as a function of

Figure 7 (p. 22). Protective HLi thickness curves.



Reactor thermal power
10^3
10^2
1
10.0
5.0
Distance from reactor to payload in m
Necessary hydride height (cm)
40
50
60
70
80

the reactor thermal power and of the distance between the reactor and the payload.

VIII. COMPARISON BETWEEN THE THERMAL REACTOR AND THE FAST REACTOR

The amount of fissionable material is not a decisive criterion from the economics standpoint. The choice of the neutron spectrum is essentially determined by the tabulation of the masses. The energy conversion circuit is the same for both types of reactors. Table 1 gives an approximate tabulation of masses.

The total is therefore about 1 ton. /24

As far as the reactor unit is concerned, the tabulation of masses is given in table 2, for both the thermal and the fast solutions.

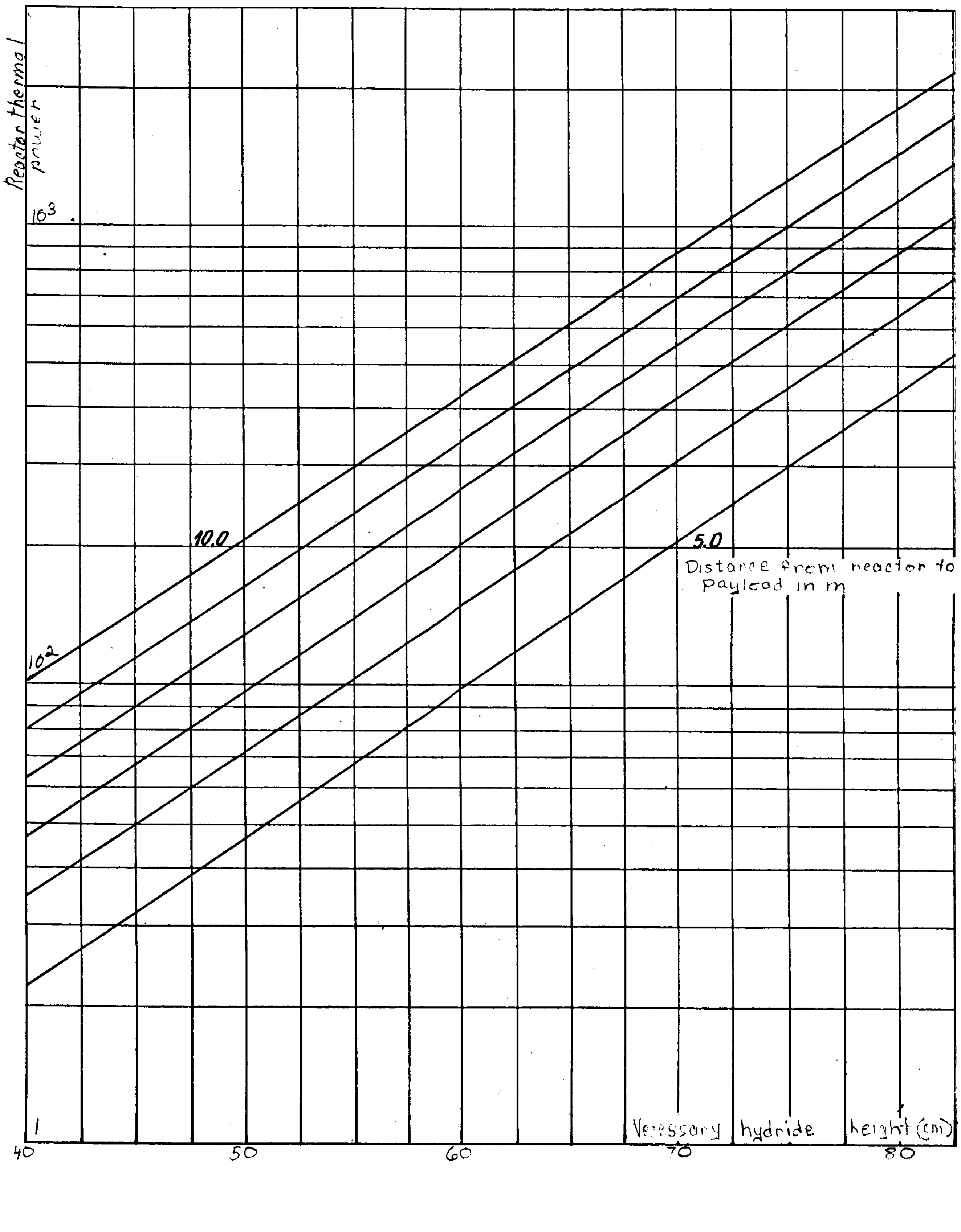
In spite of a higher density of fuel elements, the fast reactor has the weight of all the component units increased (smaller core, thinner reservoir for equal pressures), and even the weight of the protection is increased because of its lower transverse dimensions.

Figure 9 shows a comparison between the sizes of both generators (thermal and fast generators).

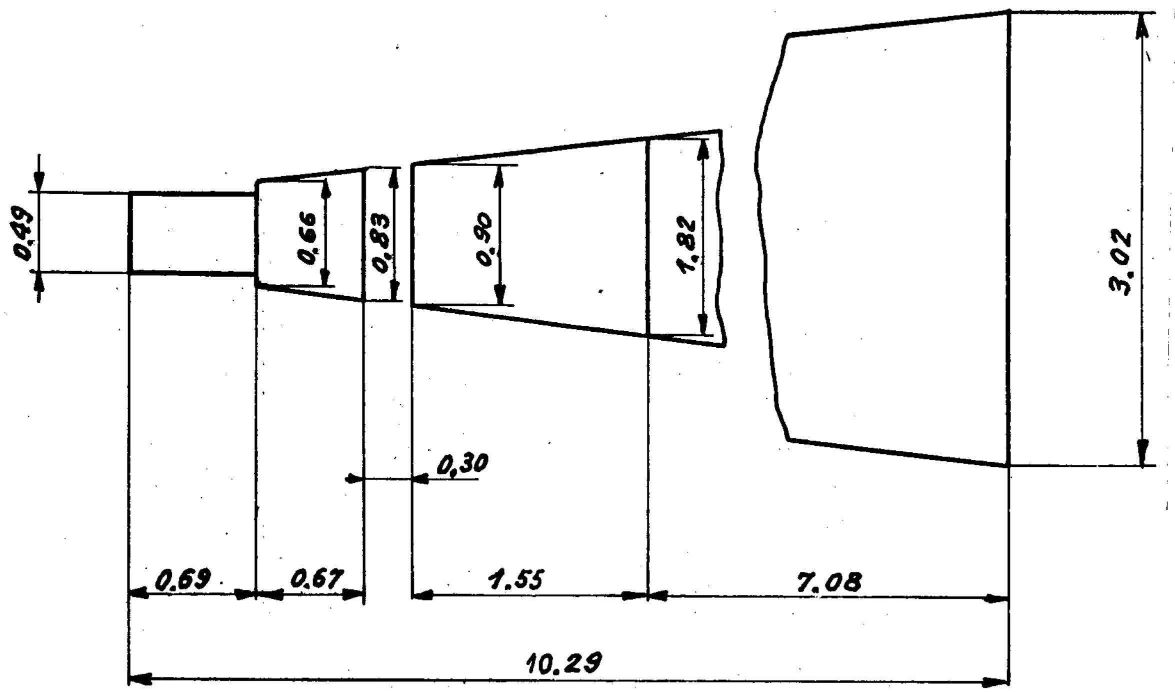
Table 3 shows the principal characteristics of a few generator projects.

Figure 8 (p. 24). Protective tungsten thickness curves.

Figure 9 (p. 25). Comparison of dimensions between the the thermal and fast reactors.


Reactor thermal power
10^3
10^2
1
10.0
5.0
Distance from reactor to Payload in m
Necessary hydride height (cm)
40
50
60
70
80

750 KWt (Thermal)



750 KWt (Fast)

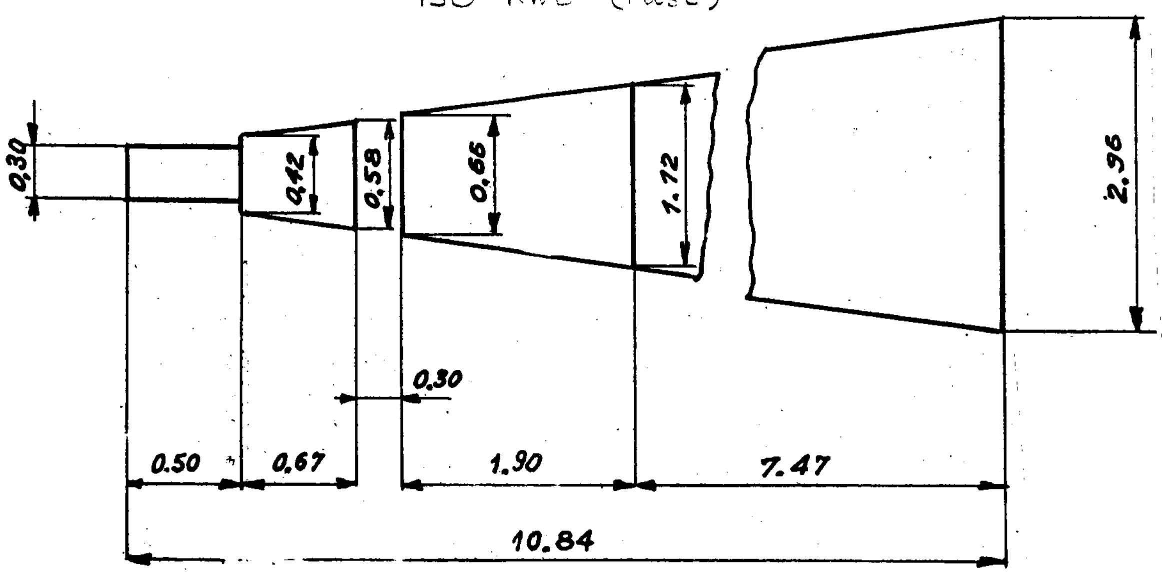


TABLE 1. TABULATION OF MASSES OF CONVERSION CIRCUIT (IN kg).

Exchangers	100
Turbine	70
Radiator	350
Alternator, pumps	220
Piping	100
Fluids	130
	970

TABLE 2. MASSES OF REACTORS (IN kg).

	Thermal	Fast
Reactor unit	340	150
Protection	290	170
Refrigerant in tank	20	10
	650	330

TABLE 3

	Generator	Electric power kW	Primary fluid	Working fluid	Neutron spectra	Reactor exit temperature ^{o}C	Radiator average temperature
1)	SNAP 2	5	NaK	Hg	thermal HZr	650	315
2)	SNAP 8	35 a 50	NaK	Hg	thermal HZr	700	305
3)	our study a)	80	NaK	K	thermal HY	850	480
4)	our study b)	80	NaK	K	fast	850	480
5)	SNAP 50	350	Li	K	fast	1100	700

The technical difficulties caused by the hydrides permit us to say /25 that for reasonable dimensions the exit temperature of 850° represents a ceiling to the thermal neutron reactor. This ceiling is obtained, as compared with zirconium hydride reactors, by changing the hydride (yttrium). This leads to a reactor of greater dimensions which is markedly heavier, and which can no longer be compared with the fast reactor in the range of power levels studied. Recall that the weight of a zirconium hydride moderated reactor (SNAP 2 and 8) if about 300 kg. It seems, therefore, that there might exist a natural association between the zirconium hydride thermal reactor and mercury as working fluid, at exit temperatures less than 700°C. Above 850-900° the fast reactor is well adapted to potassium.

IX. EXAMINATION OF THE PROBLEM FOR DIFFERENT POWER LEVELS

The above considerations apply to a power level of 750 kWth (75 kWe). We have examined the changes in the mass tabulation for different pressure levels (from 5 to 100 kW electric).

In the first approximation it can be said that the mass of the reactor remains unchanged and entails a small change of the protection weight. The mass of the conversion circuit will be practically proportional to the generator power, in spite of the fact that it is affected by the optimization of certain parameters such as the pumping power.

Figure 10 shows the mass changes per unit of power (in kg per kW electric) as a function of the produced electric power, without taking the weight of the protection into account. The curve drawn shows indeed that the usefulness of

Figure 10 (p. 28). Specific mass (kg/kWe) vs the electric power produced.

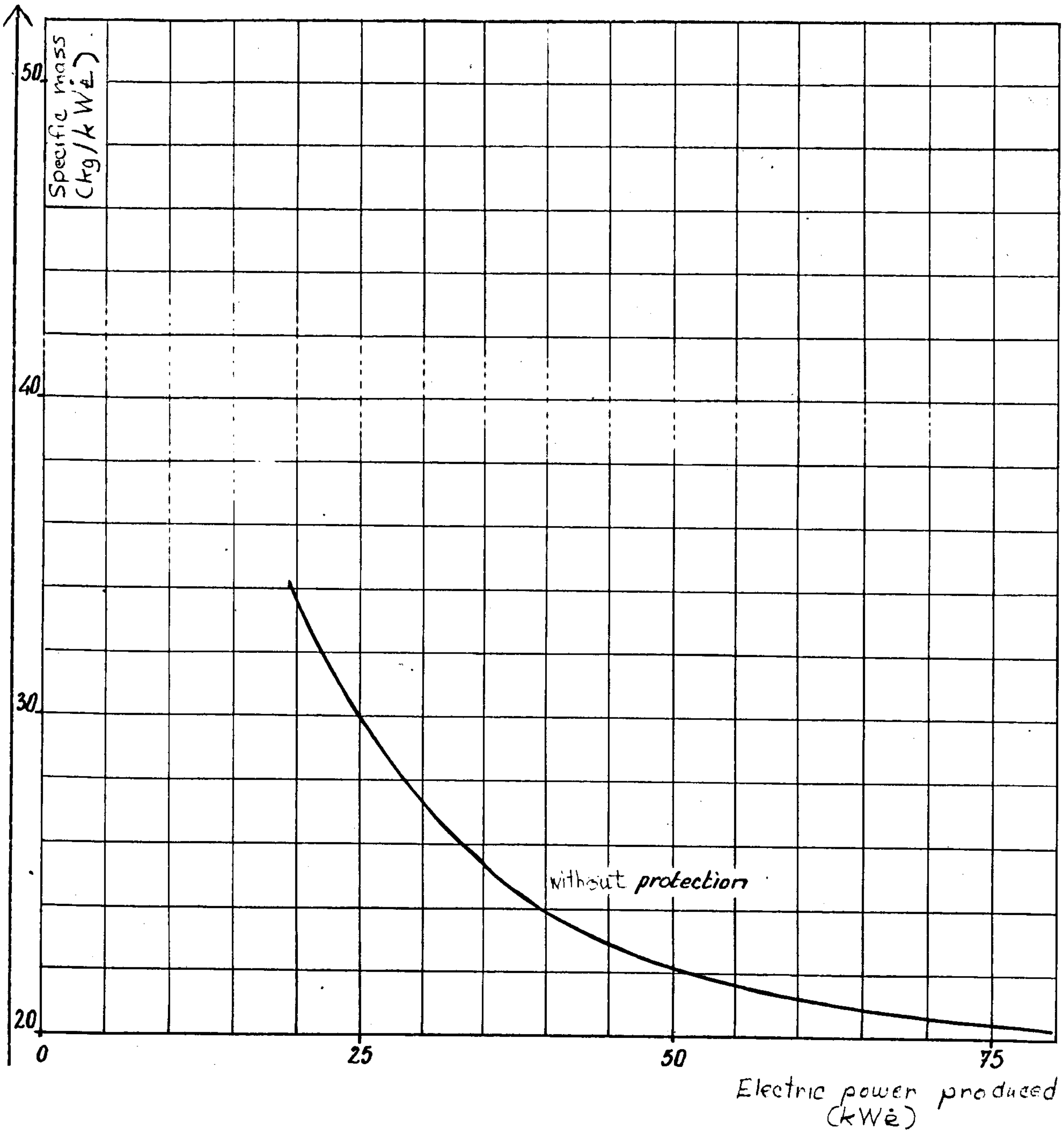


Figure 10. Specific mass curve of generator (thermal pile) as function of produced electric power (nuclear shielding not included).

the reactor increases with the desired power. In particular, below 20 kW electric, the mass per unit of power becomes sizable.

In order to have elements which can be used in a possible choice, we made a comparison between (fig. 11) the masses of the various solutions, without protection, for electric powers ranging up to 90 kW. The uncertainty regions shown in the figure originate mostly from the radiator weight. The temperatures shown are the reactor exit temperature and the radiator average temperature.

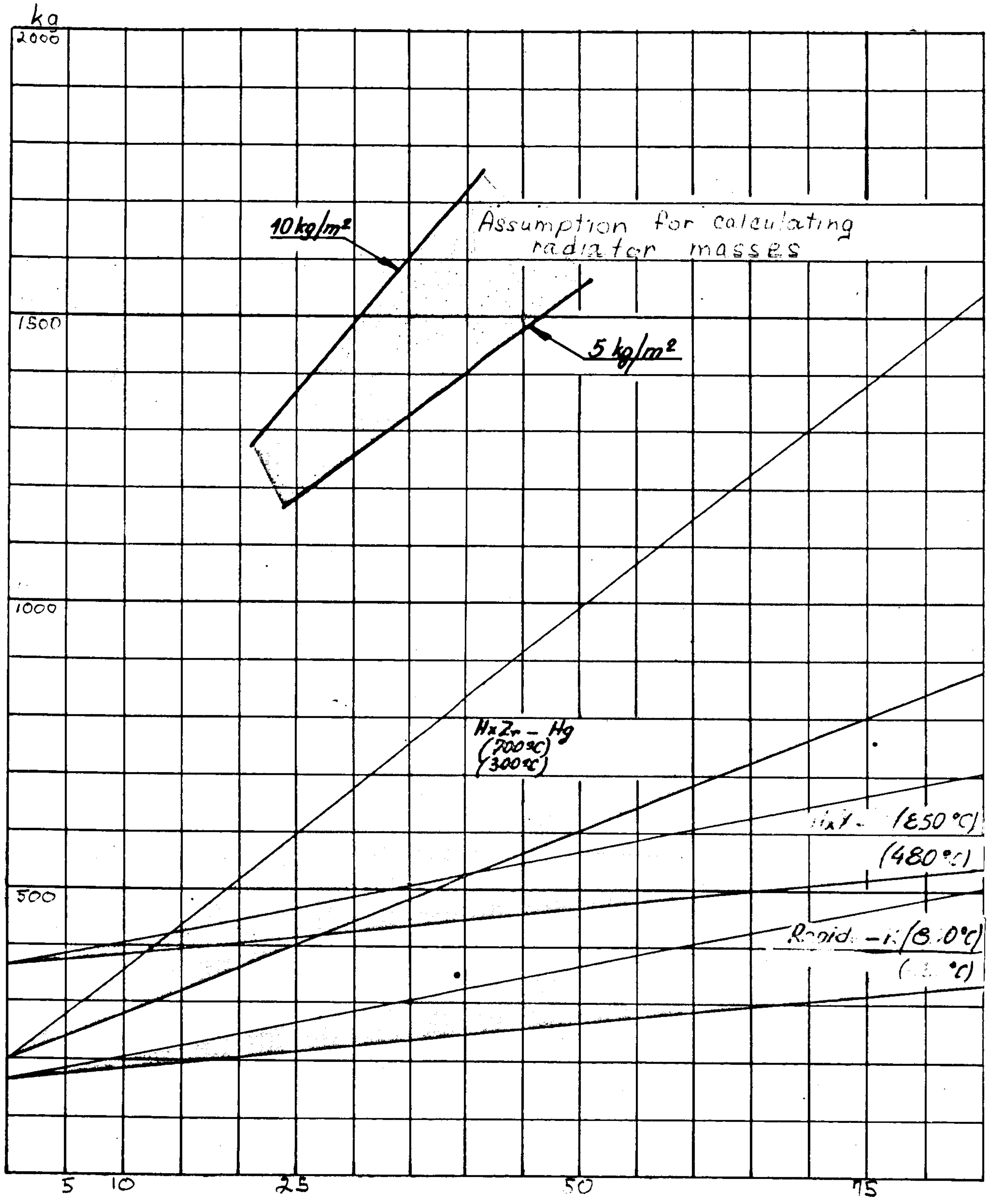
The mass of the zirconium hydride and mercury system have been deduced from the American data, in the form of a first draft. They are less than the weights obtained in fact, but they agree fairly well with the results of our study.

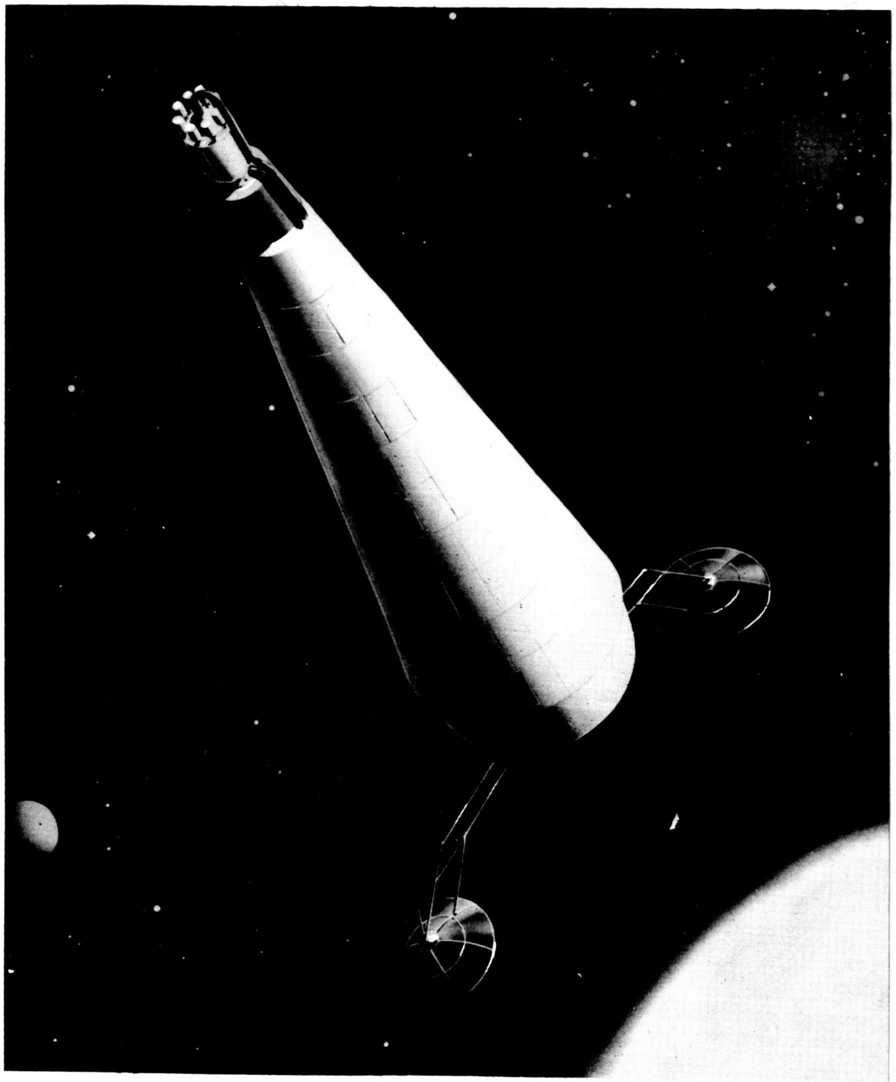
The curves obtained in this way show the lack of usefulness of the thermal neutron reactor moderated by yttrium hydride. The curves seem to favor the solution represented by the fast reactor with potassium, regardless of the electric power level desired.

This conclusion would still be valid for powers greater than some twenty kilowatts electric. For powers less than this amount the gain in mass due to the solution represented by zirconium hydride and mercury is much less pronounced because the reactor unit has the greatest mass. The gain due to the radiator is less pronounced due to the increase of temperature.

Below 10 kWe it would be safer and cheaper to choose the solution mercury and zirconium hydride, as for SNAP 2 (5 kWe), provided the use of a reactor is still justified. The problem should be more thoroughly examined.

Figure 11 (p. 30). Mass of the reactor and radiator unit vs the electric power produced.


kg
2000
1500
1000
500
10 kg/m²
5 kg/m²
Assumption for calculating radiator masses
(700°C)
(300°C)
(480°C)
5
10
25
50
75

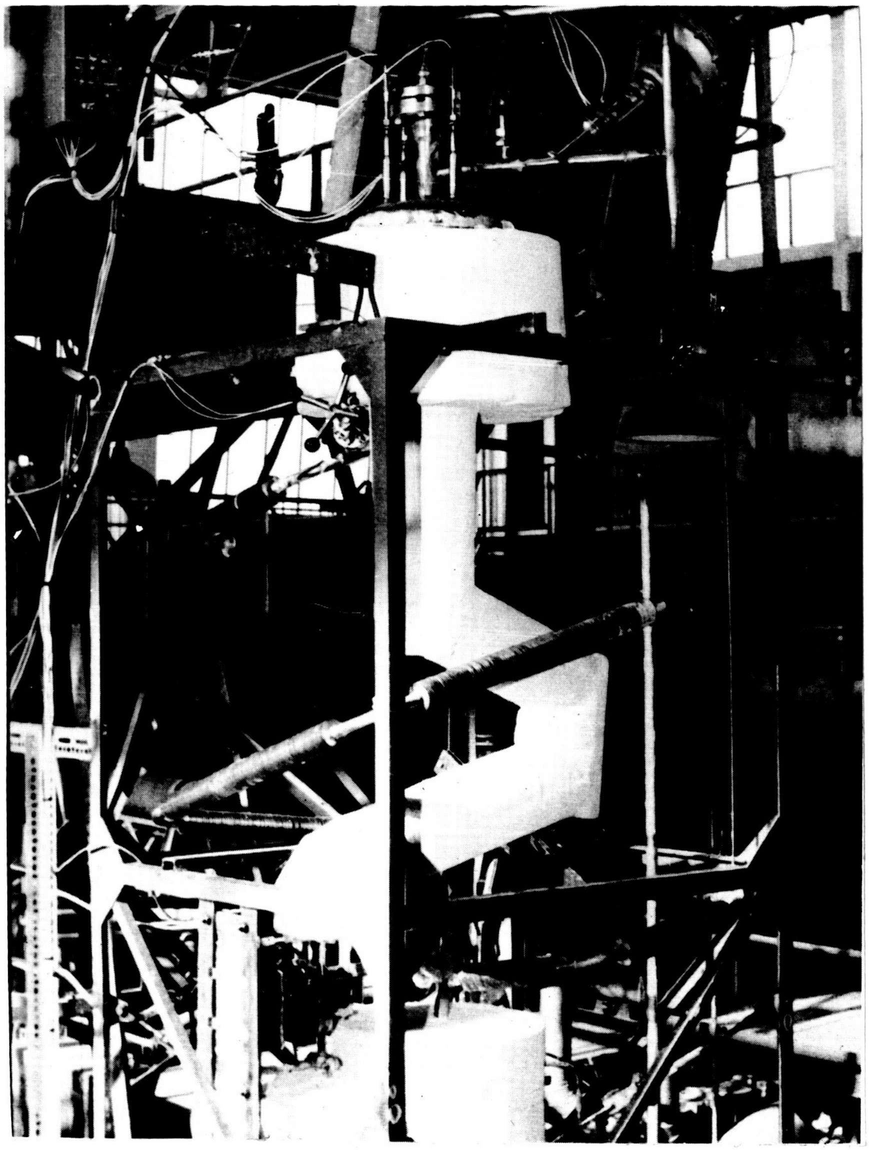


Communication relay satellite supplied by nuclear reactor.

Above 100 kWe the solution fast reactor and potassium are still valid. However, starting from a few megawatts of electric power the beryllium oxide-moderated reactor could be comparable to the fast reactor.

X. CONCLUSION

One of the objects of this study was to find out the elements necessary /28 for choosing the essential characteristics of a space electronuclear generator, in particular, the nature of the reactor and the nature of the working fluid.

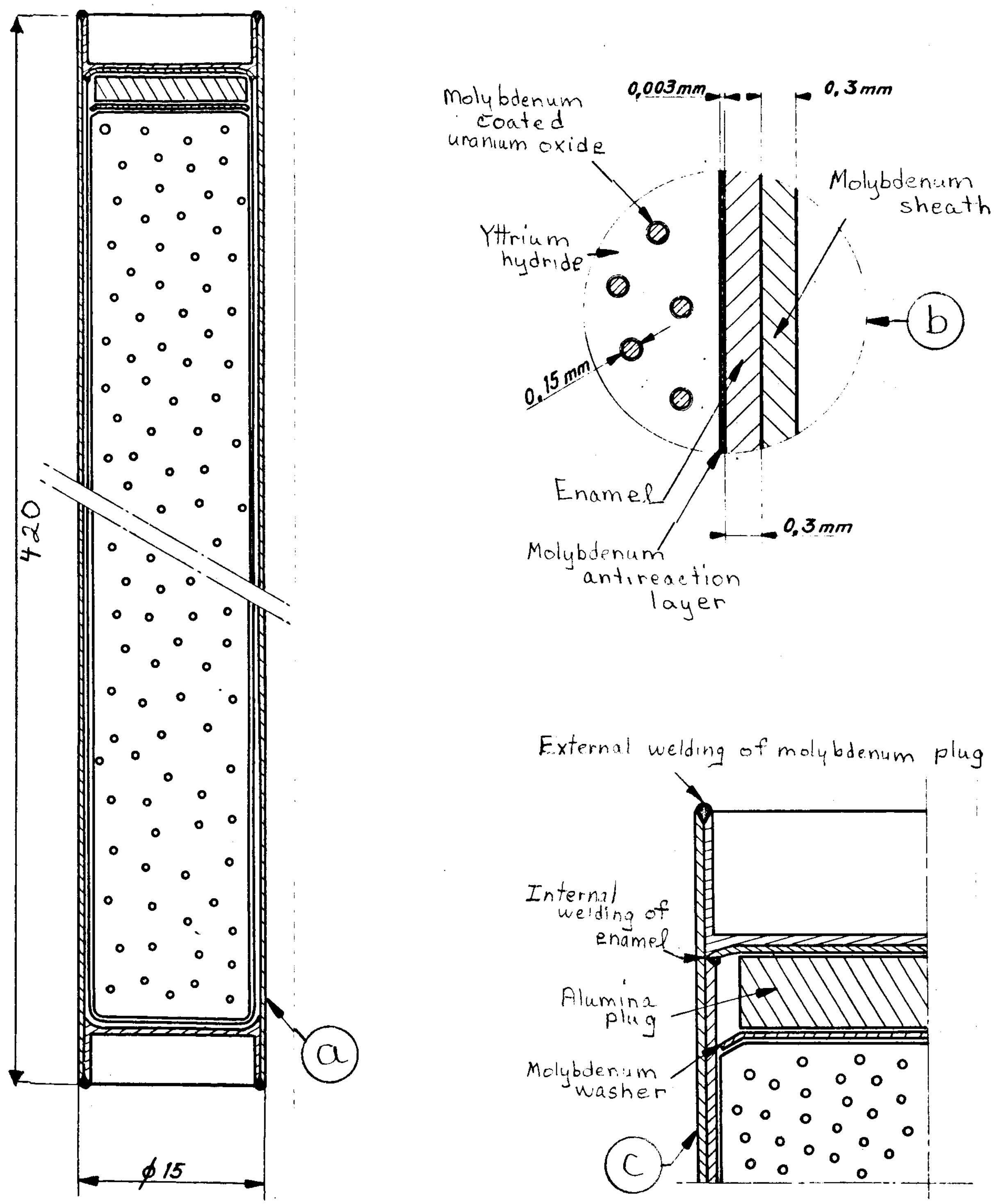


Nuclear Studies Center of Fontenay-aux-Roses, Liquid Metals Section.

NaK circuit at 950^{o}C pressurized at 3.5 bars (upper part).

A few conclusions can be drawn from the results obtained, with the reservations which apply when no experiments have yet been done.

A remark already emphasized is the increasing usefulness of the nuclear reactor as the desired power level is increased. A power threshold exists which depends mostly on the performance of the other sources of energy. Today we can talk of a few kilowatts electric.



Moderator-fuel element.

(a) Overall view.

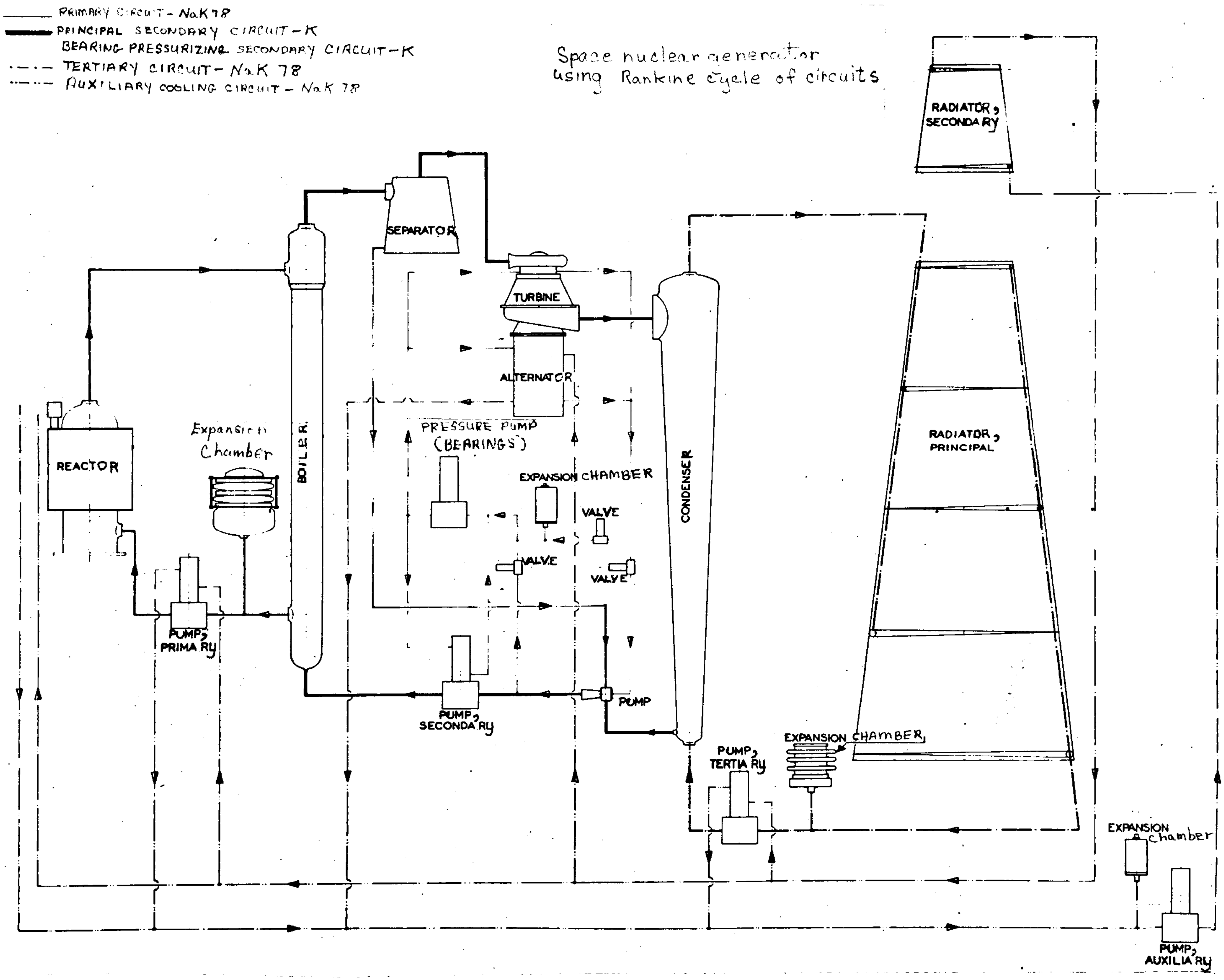
(b) Magnified view of cladding.

(c) Cladding closing arrangement.

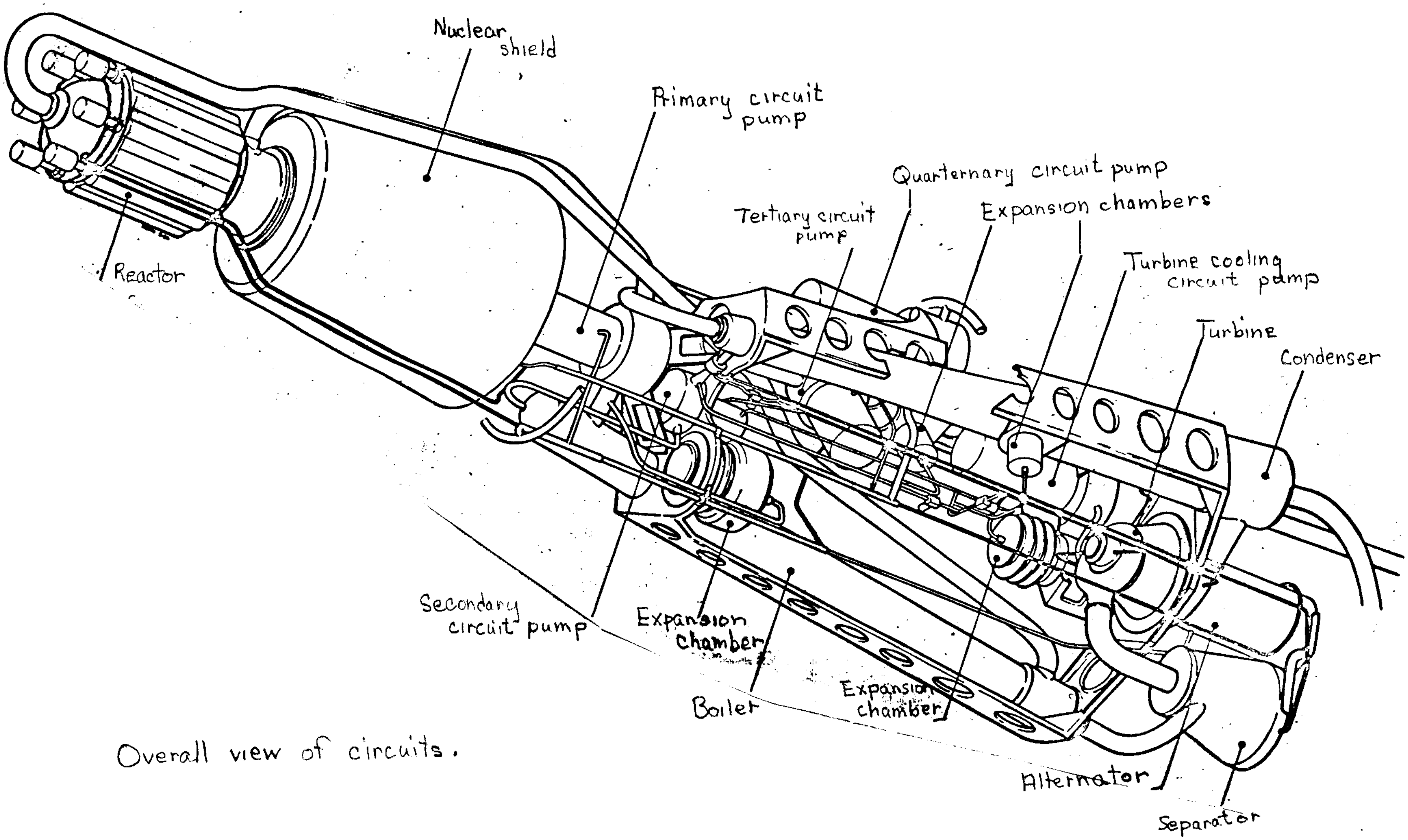
Study of Space Reactor. Arrangement of fuel elements in reactor tank.

When the temperature range of interest is examined it is observed that few satisfactory solutions exist in the neighborhood of 800°C, taking into account the nature of the cold source. An upper limit of use of the metallic hydrides and nonrefractory metals is reached. The adoption of refractory metals and of uranium monocarbide (fast reactor) would permit higher temperatures. The same applies when the working fluid is chosen between mercury and potassium.

The power levels less than 100 kW electric lead to a very small size reactor. It seems in this case that there exists a normal association between the zirconium hydride-moderated reactor and the mercury turbine on one hand,



Space nuclear generator using Rankine cycle of circuits



Overall view of circuits.

and the fast reactor and a potassium turbine on the other hand. The choice of yttrium hydride, which stands higher temperatures than zirconium hydride, leads to reactor sizes and weights appreciably greater. This solution does not seem to be of great interest.

An examination of a comparison of the mass tabulations shows that, in principle, the solution fast reactor with potassium is always more useful (fig. 11). However, for powers less than 10-15 kWe the mass differences are not sufficiently great to be decisive. The choice can be strongly influenced by the capability of the planned launcher and the state of the art of the constructor on the different problems.

The fact that the problems posed by the construction of a space nuclear generator are new would lead to a sizable amount of experimentation. It can be said, however, that the problems brought about by the energy conversion circuit have more uncertainties and require more work than the problems of the nuclear reactor.

The construction in France of a ground prototype of the hot source (reactor) and primary circuit) could be envisaged for the near future and with relatively small funds. It would only be justified provided the development of the associated programs (energy conversion system, test and launch facilities) can be insured.

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10. Working Notes and Reports Written by SNECMA within the framework of CEA Contract No. 5817/h provide the investigation and calculation methods which have led to the definition of the various generator components.

APPENDIX I

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LIST OF FIGURES

APPENDIX II

BRIEF DESCRIPTION OF THE 750 kWth SPACE GENERATOR

(The figures in the first column correspond to a thermal pile
the second column correspond to a fast pile

1. General

Available net electric power (kW)	80.7
Reactor thermal power (kW)	750
Specific mass (kg/kWe)	21/17
Overall mass (kg)	1850/1500
Overal efficiency	10.8

1.1 Primary Circuit

Working fluid	NaK
Mass per second of the working fluid (kg/s)	11.2
Core exit temperature (^{o}C)	850
Core intake temperature (^{o}C)	775
Pressure level at the pump exit (bar)	4.7
Pressure drop in the circuit (bar)	0.7

1.2 Secondary Circuit

Working fluid	Potassium
Mass per second of the working fluid (kg/s)	0.34
Turbine intake temperature (^{o}C)	770
Turbine exit temperature (^{o}C)	540
Turbine intake pressure (bar)	1.185
Turbine exit pressure (bar)	0.079

1.3 Tertiary Circuit

Working fluid	NaK
Radiator mean temperature	480°C

2. Reactor 133

2.1 Thermal Neutron Core

Set of 282 tangent rods arranged in a triangular array

Fuel: Mixture $YH_{1.7}$--Uranium at 16 volumes of hydride per volume of uranium

Uranium enrichment	90% in U 235
Rod diameter without cladding (mm)	14.8
Cladding thickness (mm)	0.25
Cladding material	Nimonic 80-A
Active core height (mm)	42
Invested uranium mass (kg)	22.8

Tank

Material	Nimonic 80-A
Inside diameter (mm)	286
Thickness (mm)	5

Reflector

Internal reflector: Be or BeO pencils of various shapes

External reflector: Material	Be
Inside diameter (mm)	296
Thickness (mm)	75

2.2 Fast Neutron Core

Set of 253 rods arranged in a triangular array separated by a helicoidal wire

Fuel	Uranium mono-carbide
Uranium enrichment	95% in U 235
Rod diameter without cladding (mm)	10
Cladding thickness (mm)	0.3
Diameter of the separation helicoidal wire (mm)	0.3
Cladding and helicoidal wire material	Niobium
Active core height	27
Invested uranium mass (kg)	65.3

Tank

Material	Nimonic 80-A
Inside diameter (mm)	189
Thickness (mm)	3.5

Reflector

Internal reflector: Be or BeO pencils of various shapes

External reflector: Material	Be
Inside diameter (mm)	196
Thickness (mm)	50

134

2.3 Thermodynamic Characteristics

Coolant temperature at the hot pipe exit (^{o}C)	889/868
Maximum cladding temperature (^{o}C)	890/870
Maximum temperature at the rod center (^{o}C)	951/1032

Average flow speed (m/s)	2.4/4.5
Average power per unit volume in the core (W/cm^3)	27.8/97
Maximum power per unit volume in the fuel (W/cm^3)	69.1/236
Average thermal flux (W/cm^2)	13.2/32.7
Maximum thermal flux (W/cm^2)	24.6/55.6
Ratio of the maximum neutron flux to the average flux	1.87/1.70

3. Nuclear Protective Shield

Material	Lithium-hydride
Height (cm)	67/67
Cladding: Nimonic 80-A, thickness (mm)	3.5

4. Turbine

rpm	24,000
Number of stages	3

5. Radiator

Shape	Frustum of cone
Angle at the apex (degrees)	14
Radiating surface area (m^2)	45.5

6. Masses (kg)

Reactor unit	340/140
Nuclear shield	290/170
Exchanger-boiler unit	104
Radiators	350
Turbine	70
Various other devices	270
Piping	96
Fluids	150
Total	1670/1350
Less (10%)	167/135
Or a total of about	1840/1500